

METHOD AND APPARATUS FOR DETERMINING AN ANGLE OF GYRATION IN A GYRATORY COMPACTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of co-pending U.S. Patent Application Serial No. 10/210,020, filed July 31, 2002, which is hereby incorporated herein in its entirety by reference.

5 BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a device for measuring a property of a gyratory compactor device and, more particularly, to a method and apparatus for determining an angle of gyration in a Superpave gyratory compactor.

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Description of Related Art

The Strategic Highway Research Program (SHRP) has developed a standard for testing the physical properties of a bituminous asphalt paving mix, using a device known as the Superpave gyratory compactor. The Superpave gyratory compactor produces
15 compacted cylindrical test samples of the asphalt paving mix for determining volumetric and mechanical properties. The compactor simulates the kneading action of the large rollers used to compact asphalt pavement during highway construction. Thus, the compacted samples simulate the density, aggregate orientation, and structural characteristics obtained in an actual roadway when proper construction procedures are
20 used in the placement of the paving mix. Typically, a sample of the asphalt paving mix is placed in an open-ended cylindrical mold, with circular disks or plugs being placed at opposite ends of the mold. The gyratory compactor device applies pressure through these disks to the sample in the mold while gyrating the mold at a specified angle to produce a

gyratory kneading action. The Superpave gyratory compactor specifications call for the mold to be gyrated at a compaction angle of 1.25 degrees, operating at 30 rpm, while applying a constant pressure of 600 kPa.

Several manufacturers produce gyratory compactors according to the Superpave
5 gyratory compactor specifications. Gyratory compactors of this type are described for example in the following United States Patents: 5,323,655; 5,456,118; 5,606,133; 5,939,642; 5,817,946; and 6,026,692.

During the compaction process, the gyratory compactor machine records the number of gyratory revolutions, the height of the test sample (or more accurately, the
10 position or movement of the pressure ram) and other parameters. In order to have consistent and reproducible results from one machine to another, each machine must be calibrated. These calibrations include measurement of the mold angle (otherwise referred to herein as the “angle of gyration” or “gyration angle”) and measurement of the pressure applied by the pressure ram. Heretofore, the mold angle calibration has been typically
15 carried out in a static mode, wherein the mold angle is mechanically set and calibrated during the initial assembly phase and not adjusted thereafter unless required. The particular method of adjustment generally differs between different machine designs, but usually involves a complex arrangement of sliding surfaces in the form of, for example, cams, pins and slots, linkages, and/or the like. The mold angle adjustment mechanism
20 thus serves to provide an offset between one end of the mold, held in alignment with the ram axis, and the other end of the mold, which is compelled to move in a circular orbit by the kinematic properties of the machine. However, a calibration carried out in a static mode will not necessarily take into account whether the configuration of the gyratory compactor maintains the mold angle within specifications throughout the entire
25 compaction process. Therefore, the angle of gyration must be occasionally verified. However, the correct angle typically can only be verified by a complete re-calibration of the machine and such a re-calibration is often not practical in the field. As such, re-calibration usually requires that the machine be shipped back to the manufacturer, or requires the presence of a factory technician at the site, each of which may involve a
30 sizeable expenditure of time and money.

In other instances, mechanical-type contact sensors have been employed to determine the mold angle. For example, U.S. Patent No. 5,817,946 to Brovold describes multiple mold angle transducers, each comprising a spring-biased plunger, wherein the tip of the plunger continuously contacts and rests against the outer surface of the cylinder wall of the mold. The relative displacements of the plungers thereby enable the determination of the mold angle. However, the compaction process is a dynamic process, with the mold being constantly gyrated while pressure is applied. Accordingly, the plungers may be prone to wear or misalignment from contact with the mold during the compaction process, thereby making it difficult to maintain calibration and receive consistent measurements from the transducers. Further, such mechanical displacement-measuring devices may not provide the necessary accuracy for measuring the mold angle in accordance with the SHRP standard. In some instances, accretions on the wall of the mold from sample processing may further decrease the accuracy of the mechanical-type contact sensors. These and other factors can affect the actual mold angle measured and indicated during the compaction process.

In addition, the pressure calibration of the machine has also been typically carried out only in a static mode. For example, a load cell can be temporarily positioned in contact with the pressure ram of the compactor to measure the force applied by the ram. However, a calibration carried out in a static mode will not take into account whether the control system of the gyratory compactor holds the pressure within specifications throughout the entire compaction process. The compaction process is a dynamic process, with the mold being constantly gyrated while pressure is applied. Also, the sample within the mold is reduced in height as it is compacted. These and other factors can affect the actual pressure applied to the sample by the gyratory compactor.

Thus, there exists a need for an apparatus, system, and method capable of statically and dynamically determining and indicating the angle of gyration of a mold as well as the pressure exerted on a sample contained therein so as to provide a consistent and readily calibrated mechanism for verifying compliance with the SHRP standard for testing the physical properties of a bituminous asphalt paving mix using a Superpave gyratory compactor, as well as other improvements over existing devices.

BRIEF SUMMARY OF THE INVENTION

The above and other needs are met by the present invention which, in one embodiment, provides an apparatus adapted to interact with a cylindrical mold for a gyratory compactor so as to determine a gyration angle of the mold, wherein the mold is adapted to contain a sample therein. Such an apparatus includes a rigid disk-shaped plate defining an axis and a periphery, the plate being further adapted to be disposed within a wall of the mold and in communication with the sample. At least one inductive sensing device is operably engaged with the plate so as to be spaced apart from and cooperable with the wall when the plate is disposed within the mold. The at least one inductive sensing device is configured to produce a signal corresponding to the angle of the wall with respect to the axis of the plate, whereby such a signal is indicative of the gyration angle of the mold.

Another advantageous aspect of the present invention comprises an apparatus adapted to interact with a gyratory compactor so as to determine a gyration angle. Such an apparatus includes an open-ended cylindrical mold having a wall defining an inner diameter, wherein the mold is adapted to contain a sample therein for compaction by the gyratory compactor. A rigid disk-shaped plate defining an axis and a periphery and having a diameter corresponding substantially to the inner diameter of the mold is adapted to be disposed within the mold in communication with the sample. At least one inductive sensing device is operably engaged with the plate so as to be spaced apart from and cooperable with the wall when the plate is disposed within the mold. The at least one inductive sensing device is configured to produce a signal corresponding to the angle of the wall with respect to the axis of the plate, whereby such a signal is indicative of the gyration angle of the mold.

Yet another advantageous aspect of the present invention comprises a system for determining a gyration angle in a gyratory compactor. Such a system includes a gyratory compactor apparatus and an open-ended cylindrical mold having a wall defining an inner diameter, wherein the mold is configured to be operably engageable with the gyratory compactor apparatus and is adapted to contain a sample therein for compaction by the gyratory compactor. A rigid disk-shaped plate defining an axis and a periphery and having a diameter corresponding substantially to the inner diameter of the mold is

adapted to be disposed within the mold in communication with the sample. At least one inductive sensing device is operably engaged with the plate so as to be spaced apart from and cooperable with the wall when the plate is disposed within the mold. The at least one inductive sensing device is configured to produce a signal corresponding to the angle of the wall with respect to the axis of the plate, whereby such a signal is indicative of the gyration angle of the mold.

Still another advantageous aspect of the present invention comprises a method of determining a gyration angle of an open-ended cylindrical mold for a gyratory compactor, wherein the mold is adapted to contain a sample therein. First, at least one inductive sensing device is inserted into an open end of the mold having a wall defining an inner diameter. The at least one inductive sensing device is operably engaged with a rigid disk-shaped plate defining an axis and having a diameter corresponding substantially to the inner diameter of the mold, wherein the at least one inductive sensing device is disposed about a periphery of the plate so as to be spaced apart from and cooperable with the wall when the plate is disposed within the mold. A signal is then received from the at least one inductive sensing device. The signal corresponds to the angle of the wall with respect to the axis of the plate as dynamically determined by the at least one inductive sensing device as the mold is being gyrated, whereby such a signal is indicative of the gyration angle of the mold.

Thus, embodiments of the present invention provide apparatuses, devices, systems, and methods capable of statically and dynamically determining and indicating the angle of gyration of a mold so as to provide a consistent and readily calibrated mechanism for verifying compliance with the SHRP standard for testing the physical properties of a bituminous asphalt paving mix using a Superpave gyratory compactor. Accordingly, embodiments of the present invention provide significant advantages as further detailed herein.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

FIG. 1 is an exploded perspective view of a mold assembly for a gyratory compactor having an apparatus for dynamically measuring the gyratory angle of the mold, according to one embodiment of the present invention;

5 **FIG. 2** is a cross-sectional view of a mold assembly for a gyratory compactor having an apparatus for dynamically measuring the gyratory angle of a mold, according to one embodiment of the present invention, and installed in a gyratory compactor;

FIG. 3A is an exploded perspective view of an apparatus adapted to dynamically measure the gyratory angle of a mold for a gyratory compactor according to one embodiment of the present invention;

10 **FIG. 3B** is a perspective assembled view of a sensing device component of an apparatus adapted to dynamically measure the gyratory angle of a mold for a gyratory compactor according to one embodiment of the present invention;

FIG. 3C is a schematic of a sensing device component of an apparatus adapted to dynamically measure the gyratory angle of a mold for a gyratory compactor, according to one embodiment of the present invention, illustrating the interaction of the sensing device component with the wall of the mold;

15 **FIGS. 3D and 3E** are perspective assembled views of a sensing device component of an apparatus adapted to dynamically measure the gyratory angle of a mold for a gyratory compactor according to an alternative embodiment of the present invention;

FIG. 3F is a schematic of a sensing device component of an apparatus adapted to dynamically measure the gyratory angle of a mold for a gyratory compactor, according to an alternate embodiment of the present invention, illustrating the interaction of the sensing device component with the wall of the mold;

25 **FIG. 4A** is cross-sectional schematic of a housing of an apparatus adapted to dynamically measure the pressure exerted on a sample within a mold in a gyratory compactor according to one embodiment of the present invention;

FIG. 4B is a cross-sectional schematic of a response to an exerted pressure of a housing of an apparatus adapted to dynamically measure the pressure exerted on a sample within a mold in a gyratory compactor according to one embodiment of the present invention;

FIG. 4C is a cross-sectional schematic of an apparatus for dynamically measuring the pressure exerted on a sample within a mold in a gyratory compactor, according to one embodiment of the present invention, illustrating the interaction of the proximity-sensing device component with a reference member mounted in the housing;

5 **FIG. 5A** is a cross-sectional schematic of a calibration device configured to allow calibration of an apparatus adapted to dynamically measure the gyratory angle of a mold for a gyratory compactor, according to one embodiment of the present invention; and

10 **FIG. 5B** is a cross-sectional schematic of a calibration device configured to allow calibration of an apparatus adapted to dynamically measure the gyratory angle of a mold for a gyratory compactor, according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are
15 shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

20 A gyration angle measurement device according to the present invention is designed to be used with any of the Superpave gyratory compactors which are presently available commercially. Illustrative but non-limiting examples of gyratory compactors which can utilize such a gyration angle measurement device of the present invention are described in the following United States Patents: 5,323,655; 5,456,118; 5,606,133;
25 5,939,642; 5,817,946; and 6,026,692.

FIGS. 1 and 2 illustrate a gyration angle measurement system according to one embodiment of the present invention, the system being particularly adapted for use with a Superpave gyratory compactor of the type described. In **FIG. 1**, a cylindrical mold **10** is configured to produce a cylindrical test sample from a sample of asphalt paving mix. The
30 mold **10** includes a cylindrical side wall **11** which is of a substantially uniform inner diameter and has open opposite ends. The particular mold **10** illustrated in **FIG. 1** has

out-turned flanges 12 adjacent to the upper and lower ends of the cylindrical side wall 11 which provide engagement surfaces cooperating with components of one particular design of a commercially available gyratory compactor apparatus so that the gyratory compactor apparatus can hold the mold 10 and impart a gyratory motion thereto.

5 However, some gyratory compactor designs do not require a flanged mold 10. Therefore, it should be clearly understood that the flanges 12 shown in FIG. 1 are not an essential part of the present invention, and the present invention can be operated with other mold designs, including those having a single flange or having no flange, or having other auxiliary elements provided on the mold to cooperate with a particular design of gyratory
10 compactor.

During the compaction process, the open opposite ends of the mold 10 are closed by removable disk-shaped plates 14, 15, otherwise referred to as “disks” or “pucks”, so that pressure can be applied to the sample of asphalt paving mix located within the mold 10 between the plates 14, 15. More particularly, a compaction ram 50 is urged into the
15 mold 10 along the longitudinal axis thereof, while the sample is simultaneously subjected to a rotating shear force resulting from the gyration of the mold 10 about the longitudinal axis with a specified tilt angle or angle of gyration, and without rotation of the mold 10 with respect to the axis. Certain of the commercially available gyratory compactor designs employ two separate and independent plates 14, 15 which are not physically
20 connected to any part of the gyratory compactor apparatus, and this is the design shown in the accompanying drawings. In other designs (not shown) the end of the compaction ram 50 of the compactor functions as one of the disk-shaped plates 14, 15. However, embodiments of the present invention are applicable to both of these variations. Further, as will be apparent from the discussion herein, the ram pressure and displacement, the
25 gyration angle, the gyration rate, and the total number of gyrations are exemplary critical parameters in the operation of the gyratory compactor apparatus.

As shown in FIGS. 1 and 2, the plates 14, 15 have an outer diameter corresponding substantially to the inner diameter of the mold 10 so as to fit loosely within the mold 10 without binding. Preferably, the plates 14, 15 have a tapered outer
30 wall 16 to accommodate the tilting and gyrating movement of the mold 10. Typically, during normal use, when the gyratory compactor apparatus is used for producing test

samples, one plate 15 is placed within the mold 10 to block one end thereof and then a measured sample of the asphalt paving mix is introduced into the mold 10. The opposite end of the mold 10 is closed by placing the second plate 14 within the mold 10 and then the assembly is placed within a gyratory compactor apparatus. Once placed into the
5 compactor apparatus, the plate 14 at one end of the mold 10 is supported or restrained, while a pressure ram 50 is moved into position bearing against the opposite plate 15 to apply a compaction pressure to the sample within the mold 10. As the pressure is being applied, the mold 10 is gyrated about an angle of gyration, in accordance with well-known techniques, for example, as disclosed in the aforementioned patents. For those
10 designs of gyratory compactors which use only a single plate, rather than a pair of plates, the mold is positioned in the gyratory compactor and either the pressure ram itself, or else a plate carried by the ram, is brought into position for applying pressure to the sample.

As previously discussed, gyratory compactors typically have an angle of gyration which is a parameter of the design and construction of the machine, wherein the angle is
15 usually set and calibrated during initial manufacture and then periodically checked and reset if necessary. The force applied by the pressure ram may also be initially calibrated and then periodically verified in a static mode with, for example, a load cell. However, the gyration angle may vary dynamically during the operation of the gyratory compactor. Further, the control system of the gyratory compactor, and/or the pressure ram itself, may
20 not hold the pressure within the required specifications throughout the entire compaction process since the compaction process is a dynamic process where the mold is constantly gyrated while pressure is applied. Also, the sample within the mold is reduced in height as it is compacted which, along with other factors, can affect the actual pressure dynamically applied to the sample by the gyratory compactor. As such, an out-of-
25 specification gyration angle or compaction pressure may often not be discovered until the periodic check of the machine, thereby presenting a risk of extensive invalid test results since Superpave gyratory compactor specifications call for the mold 10 to be gyrated at a specified angle, at a specified rpm, and while applying a specified constant pressure.

As such, embodiments of the present invention provide a monitoring apparatus
30 100 having one or more sensing devices 120 incorporated into a rigid disk-shaped plate 140. As shown in **FIGS. 1 and 2**, the apparatus 100 is inserted into the mold 10 so as to

be adjacent to either of the plates **14, 15** or the compactor ram **50**. The sample of the asphalt paving mix is disposed between the two plates **14, 15** or between one of the plates **14, 15** and the compactor ram **50**, as previously described. Accordingly, depending on the particular configuration, the apparatus **100** may or may not be in direct contact with the sample. Though the monitoring apparatus **100** is described herein as being separate from the plates **14, 15** and the compactor ram **50**, it will be understood by one skilled in the art that the monitoring apparatus **100** could, in some instances, be incorporated into any or all of the compactor ram **50** and the plates **14, 15**. As will be described further below, some embodiments of the present invention may also require that a spacer **160**, in some instances comprised of a non-magnetic material, be disposed between the apparatus **100** and either of the plates **14, 15** or the compactor ram **50**. The spacer **160** may, in some instances, be a separate component or, in other instances, may be integrally-formed with any of the apparatus **100**, the plates **14, 15**, or the compactor ram **50**.

According to one advantageous embodiment of the present invention, the apparatus **100** may be configured so as to be capable of determining the gyration angle of the mold **10**. Such an apparatus **100** is typically configured such that the plate **140** remains perpendicular to the ram axis **55** of the gyratory compactor during the compaction process, as is also generally required of the plates **14, 15**. Further, the sensing device **120** is configured with respect to the plate **140** so as to measure a proximity of a reference member **200** with respect to the sensing device **120**, as described below, wherein, when the apparatus **100** is configured to measure the gyration angle of the mold **10**, the reference member **200** comprises the mold **10** itself. Each sensing device **120** is further configured to provide an output signal corresponding to the proximity of the reference member **200** with respect to the sensing device **120**. The output signal can thereafter be correlated with the parameter being measured. For example, one or more sensing devices **120** may be configured with respect to the plate **140** such that the proximity of the mold **10** (reference member **200**) with respect to each sensing device **120**, as determined from the signals produced by the sensing devices **120**, may be monitored during the entire cycle of operation of the gyratory compactor apparatus, in both static and dynamic modes. In an appropriately configured apparatus **100**, the signals produced by the sensing devices **120** may be correlated so as to indicate

the actual gyration angle of the mold 10.

Preferably, the one or more sensing devices 120 are configured to accomplish the necessary proximity measurements without contacting the reference member 200. The benefits of a non-contacting sensing device 120/reference member 200 system will be readily appreciated by one skilled in the art. For example, a non-contacting sensing device 120 will not be affected by accretions on the reference member 200, and a non-contacting sensing device 120/reference member 200 system will not be prone to wear of either of the sensing device 120 or reference member 200 components. Accordingly, the measurements will be more accurate and measurement calibration is more readily maintained. However, though the present invention is described herein in terms of a non-contacting sensing device 120/reference member 200 system, the reference member 200 may, in some instances, contact the sensing device(s) 120, if such contact is necessary and the aforementioned shortcomings of a contacting system can be avoided.

An appropriate sensing device 120 according to the present invention is preferably configured to be non-contacting with respect to the reference member 200 and capable of determining the proximity of the reference member 200 with respect thereto. Such a sensing device 120 may comprise, for example, a Hall-effect or magnetoresistive effect transducer, each configured to be responsive to a magnetic flux. However, the sensing device 120 may also or alternatively comprise, for instance, a magnetic sensor, an accelerometer device, an electro-optical device, an inductive/capacitive device, any other suitable type of proximity sensor, or combinations of any appropriate sensors. Accordingly, though embodiments of the present invention will be described in terms of a Hall-effect type sensor, it will be understood by one skilled in the art that embodiments of the present invention may also be accomplished with various other types of sensors using the principles as disclosed herein.

Hall-effect transducers, in some common applications, are configured to measure a magnetic field and to produce a corresponding voltage signal, wherein such Hall-effect transducers will be appreciated by one skilled in the art. Basically, the Hall effect occurs when an applied magnetic field deflects charge carriers in a conductor or semiconductor material, causing a difference in electrical potential across the side of the material that is transverse to the magnetic field and the current direction. The magnitude of the Hall-

effect voltage is proportional to the strength of the magnetic field applied to the transducer. Thus, according to particularly advantageous embodiments of the present invention, an appropriate apparatus 100 may comprise, for example, one or more ferromagnetic Hall-effect transducers comprising the sensing device(s) 120, incorporated
5 within the plate 140, though other types of sensing devices may be implemented in addition to or in the alternative to the Hall-effect transducers as previously discussed. The plate 140, in turn, may then be placed into the mold 10 in such a manner as to be capable of determining the orientation of the plate 140 with respect to the inside surface of the mold 10 (reference member 200), since the mold 10 is typically comprised of a
10 ferromagnetic material. The resulting orientation of the plate 140 with respect to the mold 10 thereby corresponds to the angle of gyration of the mold 10. When incorporated in such a manner, the apparatus 100 may be used as an integral part of the mold 10 or the gyratory compactor during the compaction process so as to permit continuous measurement of the gyration angle. In such instances, the gyratory compactor may also
15 be configured to be responsive to the gyration angle determined by the apparatus 100, wherein the gyration angle may be automatically controlled and adjusted to provide the desired or required gyration angle, as will be appreciated by one skilled in the art. Alternatively, the apparatus 100 may be employed as a stand-alone angle calibration device applicable to existing gyratory compactors to permit independent measurement of
20 the gyration angle.

As shown in FIG. 3A, the plate 140 may be configured as a circular plate having a longitudinal axis 210 and comprising a cover 220 configured to engage a housing 240. The housing 240 is generally a hollowed out structure having a circular base portion 250 defining a center 255 and a periphery 260. A ring portion 280 extends from the periphery
25 260 of one face of the base portion 250 coaxially with the center 255. The outer edge of the ring portion 280 and the periphery 260 of the base portion 250 further cooperate to form a radiused edge 300 for allowing the apparatus 100 to remain perpendicular to the ram axis 55 as the mold 10, and such that the apparatus 100 does not bind in the mold 10, as the mold 10 is gyrated. The cover 220 is configured to engage the housing 240 so as
30 to be securely retained and to form a flush surface with the ring portion 280. As shown, in one embodiment, one or more spring-loaded detent ball mechanisms 320 can be

configured to interact between the cover **220** and the housing **240** so as to provide a suitable securing mechanism while still allowing the cover **220** to be removed when necessary. However, one skilled in the art will also appreciate that many other mechanisms may be used to removably secure the cover **220** with respect to the housing **240**. Since advantageous embodiments of the present invention, as described herein, implement a magnetic-type effect, the housing **240** and the cover **220** are preferably comprised of non-magnetic materials so as to minimize or eliminate interference between the sensing device(s) **120** and the reference member **200**. Accordingly, a non-magnetic spacer **160**, as previously discussed, may also be disposed adjacent to or be formed integrally with the apparatus **100** so as to minimize or eliminate interference from either plate **14, 15** or the compactor ram **50**.

In one advantageous embodiment where the apparatus **100** is configured to measure the gyration angle of the mold **10**, one or more sensing device(s) **120** may be incorporated into the plate **140** in the outer radiused edge **300** of the apparatus **100** such that each sensing device **120** is disposed adjacent to, but spaced apart from, the inner side wall **11** when the apparatus **100** is inserted into the mold **10**. In some instances, the sensing device(s) **120** may be recessed into the outer radiused edge **300** of the apparatus **100** in order to provide the desired spaced apart relation of the sensing device **120** and the inner side wall **11**. As previously described, each sensing device **120** is configured to provide an output signal representative of the proximity of the reference member **200** with respect thereto, wherein, in some embodiments, the reference member **200** comprises the mold **10** and the output signal represents the actual gyration angle of the mold **10**. As such, the apparatus **100** further comprises electronic circuitry **340** in communication with the sensing device(s) **120**, wherein the electronic circuitry **340** is configured as a receiver to, for example, sample or otherwise receive the output signal from the sensing device(s) **120** and/or convert the output signal into a corresponding digital or analog data.

In some instances, the electronic circuitry **340** may preferably also comprise a receiver component (not shown) configured to store the data such that, where provisions are included in the electronic circuitry **340** for allowing a computer device (not shown) to be interfaced therewith, the data can be read or otherwise received by the computer

device following the compaction process after the apparatus 100 has been removed from the mold 10. More particularly, for example, the data may be stored within an electronic nonvolatile memory for subsequent download after the completion of a given compaction process. In other instances, the apparatus 100 may also comprise a receiver/transmitter 5 360 in communication with the electronic circuitry 340 and capable of receiving and transmitting the data corresponding to the output signal(s) to, for example, a computer device (not shown) or other indicia or device capable of displaying the data such as, for instance, an appropriately configured LED or LCD. In one embodiment, the receiver/transmitter 360 may be configured to wirelessly transmit the data and may 10 comprise, for example, an ultrasonic wireless data transmission system or a radio frequency data transmission system. However, in other instances, the receiver/transmitter 360 may be configured to transmit the data through a wireline (not shown) or by another appropriate mechanism. In some such instances, the data may be transferred from the apparatus 100 in real time. However, one skilled in the art will appreciate that the 15 apparatus 100 may be configured to and/or may include other components for allowing the extraction of the output signal(s) or the corresponding data.

As more particularly shown in **FIG. 3B**, one embodiment of a sensing device 120 for determining the angle of gyration according to the present invention comprises a pair of Hall-effect transducers 380, 390 mounted in diametrically opposed and evenly-spaced 20 positions with respect to a soft ferromagnetic and radially-symmetric housing 400. A permanent magnet 410 is disposed about the center of the housing 400. Accordingly, in free space or in the absence of a nearby ferromagnetic metal mass, the distribution of the flux density from the magnet 410 will be radially symmetric and the transducers 380, 390 will experience equal magnitudes of magnetic flux. As such, when the sensing device(s) 25 120 is/are mounted in the plate 140 of the apparatus 100 and the apparatus 100 is disposed in the mold 10 such that the transducers 380, 390 are oriented toward the ferromagnetic inner side wall 11 and parallel with the axis of the mold 10, the transducers 380, 390 will experience substantially equal magnitudes of magnetic flux due to even spacing with respect to the inner side wall 11. That is, the transducers 380, 390 oriented 30 in parallel with the axis of the mold 10 will experience substantially equal magnitudes of magnetic flux only when the axis of the apparatus 100 is oriented in parallel with the axis

of the cylindrical mold 10 such that the lateral plane of the apparatus 100 is perpendicular to the inner side wall 11.

Thereafter, in the described configuration, if the lateral plane of the apparatus 100 is tilted or angled with respect to the inner side wall 11, one transducer 380 moves closer to the inner side wall 11 while the other transducer 390 moves further away, as shown in **FIG. 3C**. That is, the transducers 380, 390 are arranged such that an increase in the magnetic field strength experienced by the transducer 380 closer to the inner mold side 11 is accompanied by a decrease in the magnetic field strength experienced by the transducer 390 further from the inner side wall 11. The transducers 380, 390 are initially calibrated to indicate substantially equal values of magnetic field strength when the lateral plane of the apparatus 100 is perpendicular to the inner side wall 11. Thus, according to the described mechanism, the magnetic flux experienced by each transducer 380, 390 varies as a function of the angle between the lateral plane of the apparatus 100 and the inner side wall 11. As such, when the mold 10 is gyrated during the compaction process, the mold 10 moves with respect to the apparatus 100, wherein the apparatus 100 is configured to remain perpendicular to the ram axis 55 of the gyratory compactor during the compaction process, such that the transducers 380, 390 alternate between a more proximate and a less proximate position with respect to the inner side wall 11.

According to another advantageous embodiment of the present invention, one or more inductive transducer devices may comprise the sensing device(s) 120 incorporated within the plate 140. As before, the plate 140, in turn, may then be placed into the mold 10 in such a manner as to be capable of determining the orientation of the plate 140 with respect to the inside surface of the mold 10 (reference member 200). As shown in **FIGS. 3D and 3E**, one embodiment of such a sensing device 120 for determining the angle of gyration comprises a pair of soft ferromagnetic, substantially U-shaped pole pieces 381, 391 mounted in opposing and evenly-spaced relation with respect to a nonmagnetic and radially symmetric housing 401. As such, each pole piece 381, 391 generally includes a base portion 382, 392 and legs 383, 384, 393, 394 extending therefrom. Each of the base portions 382, 392 of the ferromagnetic pole pieces 381, 391 are wound with a substantial number of turns of wire, such as magnet wire, to form a coil. The coil is wound in such a manner that when an alternating current is applied through the wire, each pole piece 381,

391 exhibits the characteristics of an inductor and thus can be considered inductive transducers. Accordingly, in free space or in the absence of a nearby ferromagnetic metal mass, the value of the inductance of the coil associated with each pole piece 381, 391 (also referred to herein as the “sensed inductance”) will have a minimum value, and the pair of inductive transducers, formed by the wire-wound pole pieces 381, 391, will experience approximately equal values of inductance, assuming that each base portion 382, 392 are wound with the same number of turns of the wire.

When the sensing device(s) 120 is/are mounted in the plate 140 of the apparatus 100 and the apparatus 100 is disposed in the mold 10 such that the inductive transducers 381, 391 are oriented toward the ferromagnetic inner side wall 11 and parallel with the axis of the mold 10, the inductive transducers 381, 391 will experience substantially equal magnitudes of inductance, albeit higher values than those in free space, due to the even spacing with respect to the inner side wall 11. That is, the inductive transducers 381, 391 oriented in parallel with the axis of the mold 10 will sense substantially equal magnitudes of inductance only when the axis of the apparatus 100 is oriented in parallel with the axis of the cylindrical mold 10 such that the lateral plane of the apparatus 100 is perpendicular to the inner side wall 11. As such, in practical application, the inductive transducers 381, 391 are initially calibrated to indicate substantially equal values of inductance when the lateral plane of the apparatus 100 is perpendicular to the inner side wall 11. Thereafter, in this described configuration, if the lateral plane of the apparatus 100 is tilted or angled with respect to the inner side wall 11, one inductive transducer 381 moves closer to the inner side wall 11 while the other inductive transducer 391 moves further away, as shown in FIG. 3F. That is, the inductive transducers 381, 391 are arranged such that an increase in the inductance sensed by the transducer 381 closer to the inner mold side wall 11 is accompanied by a decrease in the inductance sensed by the inductive transducer 391 further from the inner side wall 11. Thus, according to the described mechanism, the inductance sensed by each inductive transducer 381, 391 varies as a function of the angle between the lateral plane of the apparatus 100 and the inner side wall 11. As such, when the mold 10 is gyrated during the compaction process, the mold 10 moves with respect to the apparatus 100, wherein the apparatus 100 is configured to remain perpendicular to the ram axis 55 of the gyratory compactor during

the compacting process, such that the transducers **381, 391** alternate between a more proximate and a less proximate position with respect to the inner side wall **11**.

One skilled in the art will also appreciate that, as a result of the described configurations, the respective transducers **380, 390 or 381, 391** are capable of emitting therefrom a signal indicative of the gyration angle of the mold **10**. More particularly, the gyration of the mold **10** is sensed as a proximity measurement by the transducers **380, 390 or 381, 391**, each of which thereby produces an alternating voltage output signal. The absolute value of the difference in amplitude between the voltage output signals of the transducers **380, 390 or 381, 391** at any instance during the gyration process thus corresponds to a real time measurement of the angle of gyration with respect to the inner side wall **11**. Further, in one advantageous embodiment of the present invention, an apparatus **100** configured to determine the angle of gyration includes two sensing devices **120** installed in the radiused edge **300** of the apparatus **100** in a diametrically-opposed relationship. Such a configuration may be implemented where, for example, due to wear or original tolerances between the apparatus **100** and the inner side wall **11**, the proximity of each sensing device **120** with respect to the inner side wall **11** may not be consistent throughout the compaction process as the mold **10** is gyrated. As such, using the diametrically-opposed sensing devices **120**, the output signals of the two sensing devices **120** may be monitored and averaged so as to account for any gaps or “play” between the apparatus **100** and the inner side wall **11**. The voltage output signals from the transducers **380, 390 or 381, 391** may then be received, stored, processed, and/or transmitted by the associated electronic circuitry **340**, as previously described.

According to the description of embodiments of the present invention as provided herein with respect to devices, apparatuses and systems for determining the gyration angle, it will be understood that the disclosure further supports a method of determining a gyration angle of an open-ended cylindrical mold for a gyratory compactor. For example, such a method may first comprise inserting at least one sensing device, such as a sensing device comprising one or more Hall-effect transducers or one or more inductive transducers, into an open end of a mold having a wall defining an inner diameter, wherein the at least one sensing device is operably engaged with a rigid disk-shaped plate defining an axis and having a diameter corresponding substantially to the inner diameter of the

mold. In such instances, the at least one sensing device is disposed about a periphery of the plate so as to be spaced apart from and cooperable with the wall when the plate is disposed within the mold. A signal is then received from the at least one sensing device, wherein the signal corresponds to the angle of the wall with respect to the axis of the plate as dynamically determined by the at least one sensing device as the mold is being gyrated. Accordingly, such a signal would thereby be indicative of the gyration angle of the mold.

Another advantageous aspect of the present invention comprises a monitoring apparatus 100 configured to determine the pressure applied to the sample of asphalt paving mix disposed within the mold 10 during the compaction process, as shown in FIGS. 4A – 4C, using a plate 140 having a housing 240 and corresponding cover 220, as previously described. Such an apparatus 100 may utilize a housing 240 as described above and as shown in FIG. 4A, having a hollowed out structure with a circular base portion 250 and a ring portion 280 extending from the periphery 260 of the base portion 250. As such, one skilled in the art will appreciate that, where the ring portion 280 is axially supported and a pressure is exerted across the face of the base portion 250 opposite the ring portion 280, the unsupported center 255 will experience a deflection as a result of the pressure, while the supported periphery 260 about the ring portion 280 will experience little, if any, deflection, as shown in FIG. 4B. (See, e.g., Table 24, Case 10b of Young, Warren C., *Roark's Formulas for Stress and Strain*, 6th Ed., 1989, McGraw-Hill Publishers).

Based upon the aforementioned effect and as shown in FIG. 4C, the apparatus 100 may further comprise a bar 420 mounted at the center 255 and extending toward the ring portion 280 about the periphery 260. In one embodiment, the bar 420 is nonmagnetic and may be, for example, a separate component or an extension of the circuit board on which the electronic circuitry 340 is mounted. The bar 420 includes a mounting point 430 about the center 255 and a distal end 440 at which the bar 420 ends. At least one sensing device 120 is mounted to the distal end 440 of the bar 420. A reference member 200 comprising, according to one embodiment, a permanent magnet 460, is mounted on the base portion 250 toward the ring portion 280 and about the periphery 260, so as to be in a position adjacent to the sensing device(s) 120. The bar

420 is further configured such that a deflection of the center **255** along the axis **210** of the plate **140** results in corresponding and equal displacements of both the mounting point **430** and the distal end **440** of the bar **420** along the axis **210**.

According to one embodiment, the sensing device **120** may comprise, for example, a Hall-effect transducer **480**, as previously described, mounted to the bar **420**. However, in some instances, more than one Hall-effect transducer may be used. In still other instances, the bar **420** may extend through the center **255** toward diametrically-opposed points about the periphery **260** such that a sensing device **120** on each end thereof is in correspondence with two reference members **200** disposed in diametrical opposition on the base portion **250** adjacent to the ring portion **280**. The output signals from the sensing device(s) **120** correspond to the relative proximity of the reference member **200** with respect to the sensing device(s) **120**, as the center **255** is deflected by an applied pressure. Accordingly, the output signals from the sensing device(s) **120** can be correlated with and are representative of the actual pressure conditions that exist within the mold **10** and thus the pressure exerted on the sample during the entire cycle of operation of the compactor apparatus, in both static and dynamic modes. Though embodiments of the present invention for measuring the pressure exerted on the sample are described in terms of a Hall-effect type sensor, it will be understood by one skilled in the art that embodiments of the present invention may also be accomplished with various other types of sensors as discussed above and using the principles as disclosed herein.

The various forms of sensing devices **120** disclosed herein for use with the various embodiments of the present invention may, in some instances, be affected by temperature gradients experienced by the mold **10** in the gyratory compactor during the compaction process. Such temperature gradients, during a single test, may be as large as **280°F**, with temperatures ranging from about **20°F** to **300°F**. Accordingly, a monitoring apparatus **100** according to the present invention may further be configured to measure or monitor the temperature experienced by the sensing device(s) during the compaction process, wherein the measured temperatures may be input into, for example, a temperature compensation circuit, so as to compensate or adjust for changes in output signals of the sensing device(s) **120** due to the temperature changes.

Further, in some instances, it may also be advantageous for the embodiments of the present invention to include a device **500** for calibrating the monitoring apparatus **100**. For example, where the monitoring apparatus **100** is configured to measure the angle of gyration, the calibration device **500** may comprise, as shown in **FIG. 5A**, a first cylindrical tube **520** having an inner diameter slightly larger than the diameter of the plate **140**, and a base **540**, wherein calibration device **500** is formed such that the plane of the base **540** is perpendicular to the axis of the first tube **520**. The calibration device **500** would also comprise a second cylindrical tube **560** also having a base **580**. However, the plane of the base **580** would be configured to be disposed at a desired angle with respect to the axis of the second tube **560**. For example, for a horizontally-disposed plane of the base **580**, the axis of the second tube **560** would be disposed at an angle θ of 1.25 degrees from vertical, in conformance with the Superpave gyratory compactor specifications. Accordingly, when inserted into the second tube **560**, each sensing device **120** of the apparatus **100** would provide a certain output signal corresponding to the 1.25 degree angle, as previously described. The same monitoring apparatus **100** thereafter inserted into the first tube **520**, if properly calibrated, should then provide output signals from the sensing devices **120** indicating no magnetic flux differentials, as also previously described.

Another configuration of a calibration device is illustrated in **FIG. 5B** and indicated generally by the numeral **600**. According to such an embodiment, a precision flat **620** comprised of, for example, granite, provides a flat surface on which the monitoring apparatus **100** is placed. A tubular member **640** is sized to have an inner diameter corresponding to the diameter of the mold **10**. One end **650** of the tubular member **640** is configured to be perpendicular to the axis **660** thereof, while the other end **670** of the tubular member **640** is cut at an angle θ , such as, for example, 1.25 degrees, from perpendicular to the axis **660** of the tubular member **640**. Accordingly, the flat end **650** of the tubular member **640** may be placed over the plate **140** and in contact with the precision flat **620** so as to verify an output signal from the apparatus **100** corresponding to no magnetic flux differential. The tubular member **640** can then be removed and turned over such that the angled end **670** is placed over the plate **140**. The output signal from the apparatus **100** corresponding to the 1.25 degree angle can then be verified. Such

calibration devices **500, 600** could, for example, be readily verified as providing NIST-certifiable results and would also be a simple, inexpensive, and expeditious manner of checking and maintaining calibration of the gyratory compactor device.

One skilled in the art will also appreciate, from the disclosure herein, that a calibration device for a monitoring apparatus **100** configured to determine the pressure exerted on the sample may also be provided. For example, the pressure-sensing monitoring apparatus **100** will show a certain output signal from the sensing device(s) when no pressure is exerted on the plate **140**. Accordingly, a known pressure exerted on the apparatus **100** will also produce a certain output signal whereafter, once the known pressure is removed from the apparatus **100**, the sensing device(s) **120** should return to providing the output signal indicating no pressure on the plate **140**.

Further, one skilled in the art will also appreciate that various embodiments discussed herein may, in some instances, be combined into a single monitoring apparatus **100**. For example, a monitoring apparatus **100** may be configured to determine the angle of gyration, the pressure experienced by the sample during the compaction process, and/or the temperature of the sample during the compaction process for correcting or adjusting the data collected from the sensing device(s) **120**. More particularly, in one instance, a monitoring apparatus **100** may be configured to determine the angle of gyration, as discussed above, but may also include sensing device(s) **120** mounted on a bar **420**, adjacent to a reference member **200**, as discussed with respect to the configuration for measuring the pressure experienced by the sample. However, if such a combination apparatus **100** is configured to implement, for example, a magnetic-type sensing device **120** such as a Hall-effect transducer or an inductive-type sensing device such as an inductive transducer, the apparatus **100** must also be configured to minimize interference between the different mechanisms. For instance, the bar-mounted sensing device(s) **120** mechanism for determining pressure may be oriented perpendicularly or at a lesser angle to the sensing devices **120** used to determine the gyration angle. In other instances, for example, magnetic shielding (not shown) may be included within the plate **140** for appropriately isolating the different mechanisms, as will be appreciated by one skilled in the art.

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. For example, the monitoring apparatus **100** may also be configured to monitor additional parameters within the mold **10** or associated with the asphalt paving mix during the compaction process. Further, one skilled in the art will appreciate that the inductive transducer devices comprising the sensing device **120**, as shown in **FIGS. 3D-3F** may be specifically implemented in a plate **140** as shown in **FIGS. 1, 2, 3A, 4A-4C, 5A, and 5B**, though the plate **140**, components operably engaged therewith, and/or other devices such as the calibration devices **500, 600** may have to be modified over the illustrated configuration(s) of a plate **140** implementing a Hall-effect transducer device as particularly shown in **FIGS. 3B and 3C**. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.